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LEXINGTON PROJECT REPORT

No. 144

# PROBLEMS OF FULL-SCALE TESTING OF NUCLEAR POWER PLANTS FOR AIRCRAFT

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ABSTRACT ........

## DISCLAIMER

Lexington Project Report #144

Subject: Problems of Full-Scale Testing of Nuclear Power Plants for Aircraft
Author: Addison Rothrock
Place: Lexington
Date: September 3, 1948

## INTRODUCTION

In the development of conventional aircraft power plants, several engines of the model under consideration are evaluated through test runs and subsequent tear-downs and inspections before the engine is flown. Experience has shown that it is also advisable to determine the performance of the engine at altitude before using the engine as the motive power for an airplane. Such work is either done by placing the test engine in a multi-engine aircraft so that failure of the test engine will not unduly jeopardize the airplane or, preferably, by doing the work in an altitude wind tunnel or an altitude tank.

Such altitude equipment is available at the Cleveland laboratory of the NACA for investigating engines of about 5000 pounds thrust up to altitudes of 60,000 feet and at Mach numbers, in the higher altitude range, of greater than 1. The NACA is expanding this equipment to accommodate engines of greater power. The United States Air Force is considering the construction of an aircraft engine development center at which facilities also will be provided for testing, at altitude conditions, jet engines of higher power than those now being built. Furthermore, the Navy is planning the construction of facilities for testing compressors and turbines of fairly large size under altitude conditions. Similar equipment is being installed at several of the industrial plants where turbojet engines are being manufactured. Consequently, the equipment necessary for research, development and testing of the components of the nuclear-powered aircraft engine, exclusive of the reactor, either is available or probably will be available as part of the current program for the development of aircraft engines.

Considering the reactor, the situation is quite different. First, there is no equipment available for work on the complete reactor, and second, the concept of such work is not similar to the procedures employed in conventional engineering development. With the reactor, the unit cannot be run at successively higher powers with periodic tear-downs, inspections and necessary replacements.

## OPEN-CYCLE REACTOR

1. The following study of the procedures and costs involved in the testing of full-scale reactors suitable for aircraft use is based on the performance of the open-cycle (turbojet) engine as analyzed by NACA. The engine conditions used for flight conditions of 30,000 feet altitude and Mach number of 0.9 are

| | |
|---|---|
| pressure ratio of compressor | 40 |
| pressure ratio across reactor | 1.354 |
| reactor wall temperature | 2500° R |
| turbine inlet temperature | 2000° R |
| intercooler effectiveness | 0.50 |

For these conditions a thrust of 33.5 lb. per lb. of air per second is obtained. Thus a 15,000 lb.-thrust engine requires an air flow of 450 lb./sec. and a 45,000 lb.-thrust engine requies an airflow of 1350 lb./sec. The airflow of these engines would be doubled at sea level static conditions.

Compressor tests require only drive motor and gear box, cooling tower and water pumping equipment for the compressor intercooler. Although refrigerated air is frequently used in fundamental compressor investigations, it is not required to determine generalized compressor characteristics. Turbine tests require a compressed-air supply, air-heating equipment and absorption dynamometers. Exhauster equipment is not absolutely required for the turbine inasmuch as the turbine discharge pressure at the design condition is above sea level pressure. If the compressor and turbine of the subject engine are divided into four or more units, the airflow per unit will be within the range of the flows for which equipment will probably be available either in the laboratories of the NACA or of the National Military Establishment.

2. Four systems have been considered for conducting full-scale reactor tests. The first of these, System I is represented schematically:

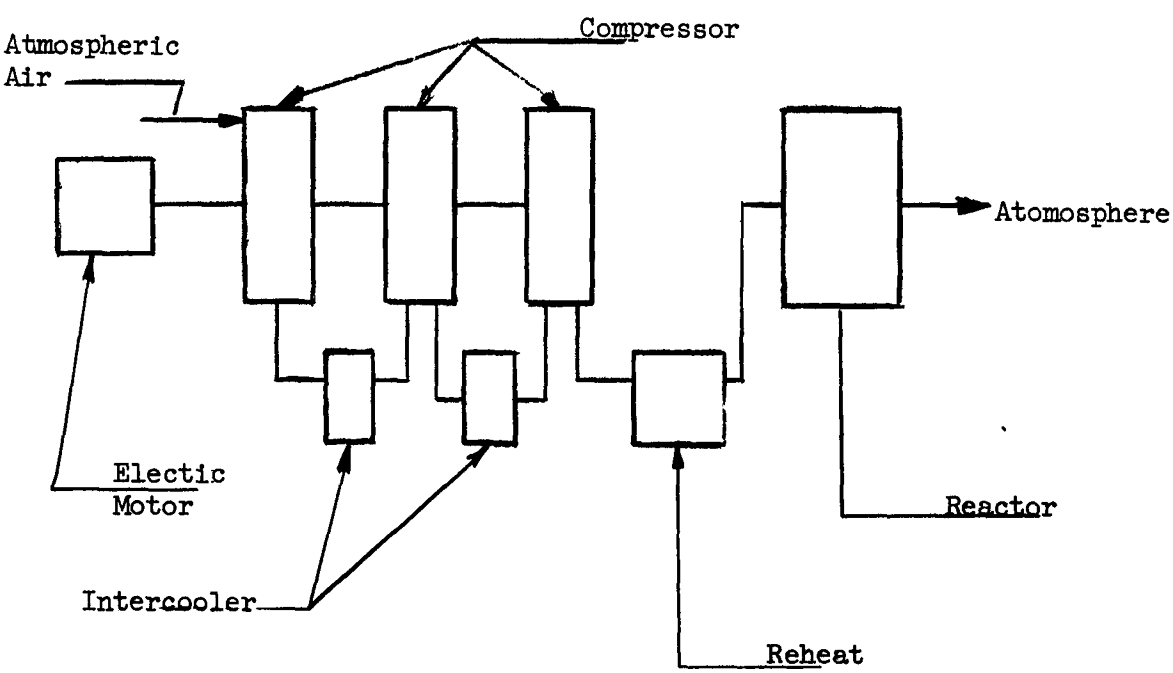


Figure 1

It consists of an electric motor(s) driving 3 stages of commercial compressors with water-cooled intercoolers between stages of the compressor and a reheat unit for raising the compressor discharge temperature to the value (1200° R) obtained in the actual engine. The air is discharged to the atmosphere after passing through the reactor. Consequently there is no fission-product contamination of machine parts in case of fuel rod failure. The use of sea level air at the compressor inlet requires an overall compressor pressure ratio of 19 in order to simulate the discharge pressure corresponding to a pressure ratio of 40 at 30,000 ft. altitude, M = 0.9. If the reactor is to be tested for sea level performance a pressure ratio of 40 is of course required and can be obtained by addition of another compressor stage. The pressure ratio per stage has been chosen high enough to account for intercooler and duct pressure losses. The results of the cost estimate for System I are tabulated below for the 45,000 lb.-thrust engine, M = 0.9

| | 30,000 ft. alt | sea level static |
|---|---|---|
| air flow, lb./sec. | 1350 | 2700 |
| effective comp. pressure ratio | 19 | 40 |
| compressor power, HP | 355,000 | 883,000 |
| Item | | |
| compressor and gear, cost | $6,000,000 | $16,000,000 |
| motor and switch gear, cost | 7,500,000 | 18,000,000 |
| intercooler, cost | 700,000 | 2,000,000 |
| cooling tower, cost | 200,000 | 500,000 |
| pumps & pipes (water) cost | 75,000 | 225,000 |
| reheat equipment | 550,000 | 1,250,000 |
| building & extras | 3,775,000 | 10,000,000 |
| Total | $18,775,000 | $47,975,000 |

The above costs would be divided by 3 for the case of the 15,000 lb.-thrust engine. The foregoing estimates do not include any allowance for transmission lines, substations and roads -- the costs of which would depend on the site chosen for the laboratory -- nor do they include any emergency compressor-drive equipment which may be considered necessary to provide for the contingency of equipment failure during tests.

If electrical power is to be used, the sites at which the installation can be placed are more or less limited to the large hydraulic power locations, such as the Columbia River Basin, Boulder Dam area or possibly the Tennessee Valley. Because of the hazards involved in such a reactor it must be located at distances from any major strategic centers according to the requirements set forth by the Reactor Safeguard Committee.

3. System II is similar to System I except for the substitution of a gas-turbine system for the electric motor drive. Hot gas for the turbine would be obtained from the reactor discharge; thus the system would be similar to the actual aircraft turbojet engine for which the reactor is

designed. The compressor and turbine would, however, be of commercial design (similar to the compressors of System I) instead of aircraft design. No cost estimates for gas turbines of the size required are readily available, however, considering that the turbine cost would be about the same as the compressor cost; the total cost of System II would be about the same as of System I (inasmuch as the compressor cost was about equal to the electric motor cost in System I). In case of a fuel-rod failure, the turbine system is subjected to fission products. This disadvantage is removed by using System III.

4. System III is similar to System I and II except for use of a steam-turbine drive instead of electric motor or gas-turbine drive. In this system the gas discharged from the reactor is passed through a heat exchanger, which provides some of the heat required for the steam cycle and then discharges to the atmosphere. The steam passes from the heat exchanger, through an auxiliary heater, through the steam turbine and then to a condenser from whence it is pumped back to the heat exchanger. Additional heat to that contained in the reactor discharge gas is required to provide the required steam turbine power because the reactor discharge gas is limited to a temperature of 2000° R. The gas turbine of System II does not require additional heat because the pressure energy of the gas is utilized whereas in the steam cycle of System III only the temperature energy of the gas is utilized in the heat exchanger. A rough estimate indicates that System III would cost about 25 to 50 per cent more than System I because of the heat exchanger, reheating equipment, and heat dissipating (cooling tower etc.) equipment required.

5. System IV consists of a wind tunnel arrangement as shown schematically below:

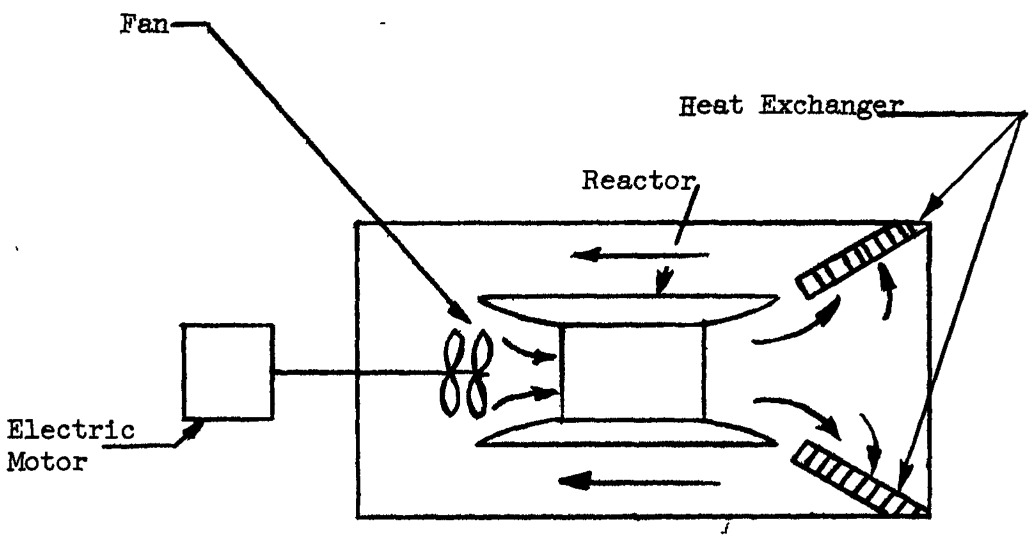


Figure # 2

The tunnel can be pumped up to the desired pressure and the fan or blower need provide only sufficient pressure rise to overcome the pressure losses through the reactor, heat exchanger and tunnel passages. The heat exchanger must remove all of the reactor heat output plus the fan power. The variable-density tunnel type of construction has been chosen because of the high pressures desired. For the case of the 45,000 lb.-thrust engine at 30,000 ft. altitude, M = 0.9, the fan power was calculated to be 67,500 HP and the heat-exchanger heat dissipation was 330,000 Btu/sec. The cost estimate is tabulated below:

| | |
|---|---|
| motor drive | $ 2,400,000 |
| fan | 150,000 |
| heat exchanger | 600,000 |
| cooling tower | 350,000 |
| pumps for water | 150,000 |
| tunnel shell & structure | 300,000 |
| building and extras | 1,000,000 |
| Total | $ 4,950,000 |

For testing the reactor at its sea level output the above figure should be multiplied by about 2.5, ($12,500,000). If it is desired to shield the entire tunnel shell with about 4 feet of concrete, an additional $125,000 would be required.

6. System V consists of testing the reactor with the turbines to be used in the completed aircraft power plant. This system is obviously the cheapest, but probably presents the greatest hazard because of the lightness of construction of the components. The decision as to whether or not to use System V will depend on the reliability of the units.

## CLOSED-CYCLE ENGINE

In the closed-cycle engine the problem of testing the reactor is simplified because the conditions within the reactor are less affected by the altitude. So far as the reactor is concerned, altitude operation constitutes lower flow rates of the cooling medium than is the case at sea level. The pressures and temperatures at which the cooling medium operates can be independent of altitude except as the rates of flow affect the pressure drop in the reactor. The power required to pump liquid metal, such as bismuth, through the reactor is of the order of 1% of the reactor output. The power required to pump the helium to the reactor is of the order of 10% of the power output. Comparing with the air-cooled reactor, it is noted that in the case of air cooling the power required to compress the air is approximately one-half to equal the reactor output. In developing the closed-cycle reactor, the power requirements need not be considered in establishing the location. However, the cooling requirements are severe. The amount of heat to be extracted is, of course, the total reactor output. The cooling could be provided by either an air system or by water. In the latter case, a secondary or intermediate coolant might be required.